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ABSTRACT

The use of fuels thickened by gelation or emulsification has been proposed for reducing the hazards of fuel fires caused by aircraft crashes. This investigation was conducted primarily under a contract issued by the Federal Aviation Administration to determine the feasibility of utilizing gelled or emulsified fuels in a four-engine jet transport fuel system. A comparative screening of the rheological and physical properties of several modified fuels resulted in a selection of the most promising candidates for further study. A partial DC-8 (Model 62) aircraft fuel system was used in the test program to provide data for system analysis using the selected fuels. Results of the test program indicated that an unmodified commercial jet aircraft fuel system cannot effectively utilize the gelled and emulsified fuels examined.

THE INVESTIGATIONS described in this paper were primarily funded by the Federal Aviation Administration (FAA). Contributions from independent studies by the Douglas Aircraft Co. have been offered to enhance the final results of the continuing FAA investigations into the use of gelled and emulsified fuels for reducing the hazards of fuel fires caused by aircraft crashes. The areas of examination were extended to cover a complete four-engine jet transport fuel system.

Several gels and emulsions under study by the industry were considered; however, only one gel and one emulsion were selected for full-scale testing and systems performance analysis. Problem areas which could result from using these fuels in current aircraft fuel systems are identified and possible solutions are discussed. Ground testing programs are outlined which screen fuel systems intended for flight testing with modified fuels or examine a fuel system for compatibility with a candidate fuel.

SELECTION OF CANDIDATE FUELS

Laboratory testing was undertaken to provide data on modified fuels, which included three gels and three emulsified fuel formulations. This testing produced rheological data used in screening fuel characteristics. Fig. 1 is typical of the shear stress/shear rate curves obtained. Fig. 2 shows the variation of yield stress with temperature for three of the fuels examined.

A summary of fuel properties and other available information was made to assist in selecting one gel and one emulsion for the subsequent phases of the test program.

EMULSIFIED FUELS - One criterion for the selection of an emulsion was that it be capable of being tested over a range of yield stresses from approximately 500 to 2000 dynes/sq cm. This range provides a maximum separation of data points with a fuel of constant composition and, thus, more confidence in the extrapolation of results. It was also felt that low yield stress value would be required of a fuel to be compatible with existing fuel systems. One candidate emulsion in the relaxed condition could attain only a yield stress of 1200 dynes/sq cm, whereas the emulsion selected attained a yield stress of 600 dynes/sq cm.

The third emulsion was eliminated because a suitable formulation was not available at the time. Thus, one emulsion remained which is hereinafter referred to as emulsified fuel B.

It was originally intended to use an emulsion whose yield stress could be varied over a desirable range in order to obtain full-scale fuel system test data for various yield values. At this time, there were no data available to compromise this approach. However, full-scale test data revealed that "working"

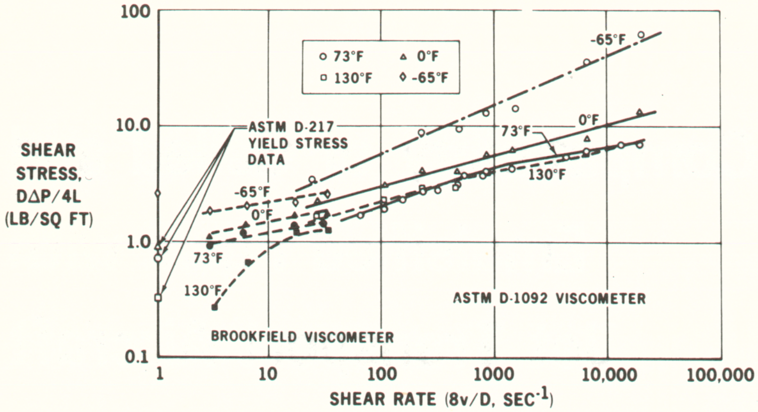

Fig. 1 - Gelled fuel A flow diagram

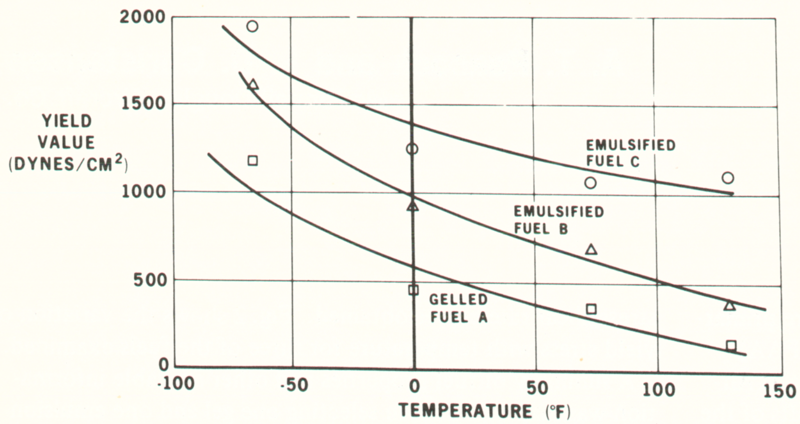

Fig. 2 - Effect of temperature upon yield values

the fuel to the desired yield stress level would not result in consistent fuel flow results. Other investigators conducting similar testing also were experiencing anomalous results.

A test program to resolve the problem was not within the scope of the present investigation; therefore, it was agreed that current analysis would be based on test data obtained from emulsified fuel B.

GELLED FUELS - The first gelled fuel tested was the only currently developed gel which had a rapid recovery after being subjected to shear. The gel also had shown promise in safety tests. In addition, its cohesive properties indicated that fuel adhesion to the tank surface would be minimal and thus result in the least unusable fuel.

After this gel had been tested for rheological properties, the fuel vendor supplied a new gelled fuel formulation. This gel was free of the metallic compounds found in the gel being tested and, in addition, the amount of resin was reduced to approximately 2%. It is not known whether other compositional changes were made as the resin gellants are proprietary. Although both fuels are similar in appearance, there are rheological differences. The new gel cannot be measured for yield value with the 30 gram cone penetrometer and the viscosity is much lower. The Federal Aviation Administration (FAA) directed the Contractor to use the new gel (gelled fuel G) in subsequent testing.

FUEL/COMPONENT TESTING

Pressure drops were determined for several fuels during the full-scale fuel system testing. The use of pressure transducers is required when making short test runs with these non-Newtonian fluids. The test setup is shown schematically in Fig. 3. Fig. 4 shows that the gelled fuel G flow curve crosses the liquid JP-4 fuel curve at a flow rate of approximately 500-600 lb/min. This may be due to a prolongation of laminar flow with the thicker fluid. The slope of the curve is actually much flatter than a laminar line and appears to start from a high yield point and then move into either a laminar or turbulent flow characteristic. Tests at high flow rates may show that the curve will come back into a turbulent line.

The effect of varying the yield stress of the emulsion is shown in Fig. 5. The top three curves are for a sample of emulsion which was first tested in its relaxed state at a yield stress of 785 dynes/cm^2. This sample was immediately "worked" to an intermediate yield stress of 1475 dynes/cm^2 and then subjected to the pressure drop test. Following this test, the yield stress was increased to 1850 dynes/cm^2 and the test repeated. The lower curve is for a sample of emulsion which had been used in several tests prior to being tested at 1475 dynes/cm^2.

The gel G fuel sample was becoming less viscous after repeated testing. The test data were evaluated by determining the pressure drop of a component, first with the used fuel sample, and then with a new fuel sample. The new sample was recycled through the component to investigate the period required for breakdown as shown in Fig. 6. The effect of gel breakdown during testing was found to be negligible.

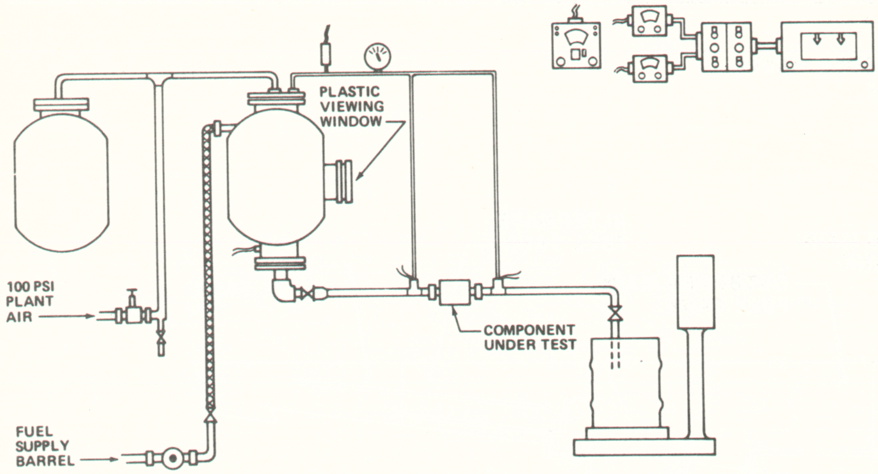

Fig. 3 - Component pressure drop test setup

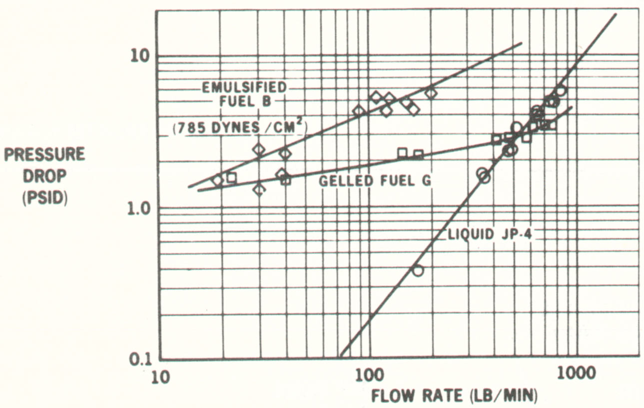

Fig. 4 - Line pressure drop (1-1/2 in., 0.035 wall, straight A1 tube, 10 ft long)

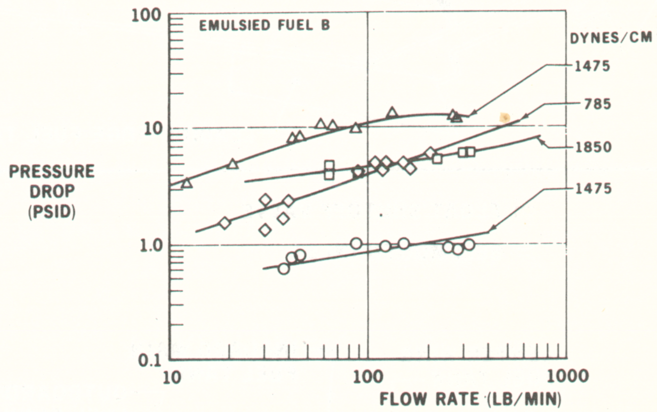

Fig. 5 - Effect of varying yield stress on pressure drop (1-1/2 in., 0.035 wall, straight A1 tube, 10 ft long)

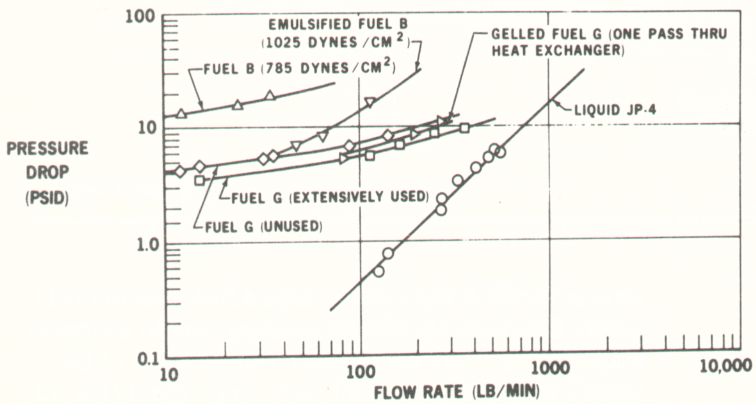

Fig. 6 - Component pressure drop (heat exchanger)

SYSTEMS ANALYSES

The several fuel subsystems of the airplane were analyzed for performance with the two fuels selected (emulsion B and gel G).

FILL SYSTEM - Fill system (Fig. 7) analyses were conducted to estimate the initial fill rates and fill times using the modified fuels. Supply pressures of 50 psig were assumed. Ground servicing equipment modifications were not considered at this time. Table 1 shows the fill analysis summary.

VENT SYSTEM - Commercial aircraft vent systems (Fig. 8) are frequently sized by the allowable limits on tank pressure during overfill. Limits were exceeded by approximately 10 psi with either fuel.

The fuels showed a tendency to trap the vapor and air bubbles which form when the fuels are subjected to a partial vacuum. These bubbles expand as the pressure is reduced and cause an expansion of the fuel mass. The ability to trap bubbles varies with the particular fuel, as shown in Fig. 9. Emulsion B is shown to expand to over 125% of its original volume.

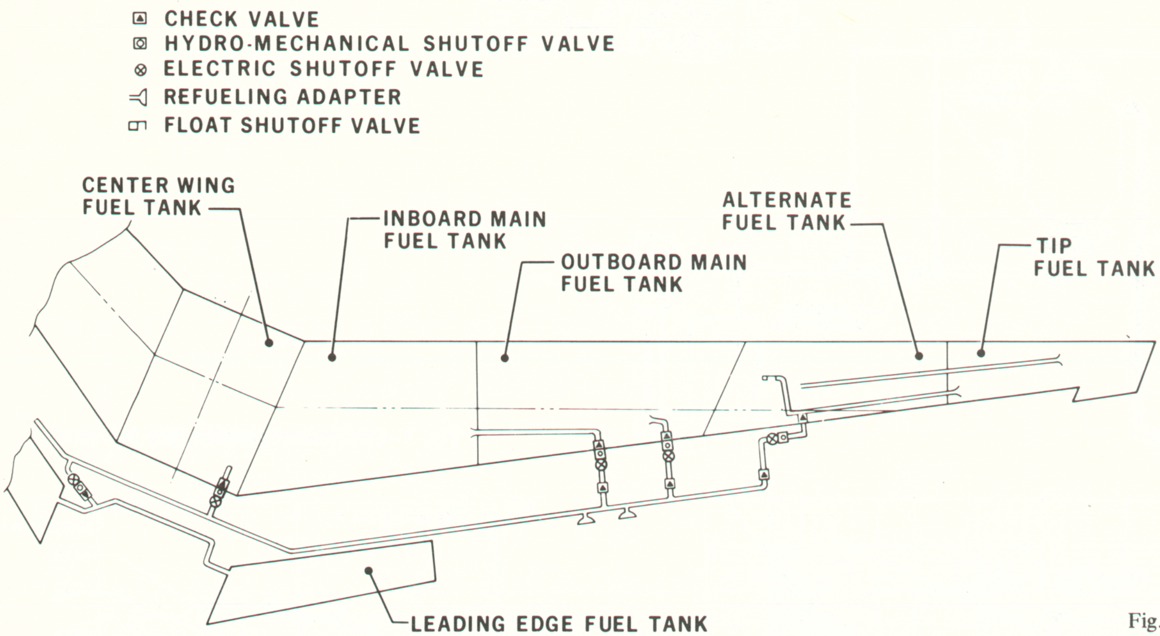

Fig. 7 - DC-8 fill system

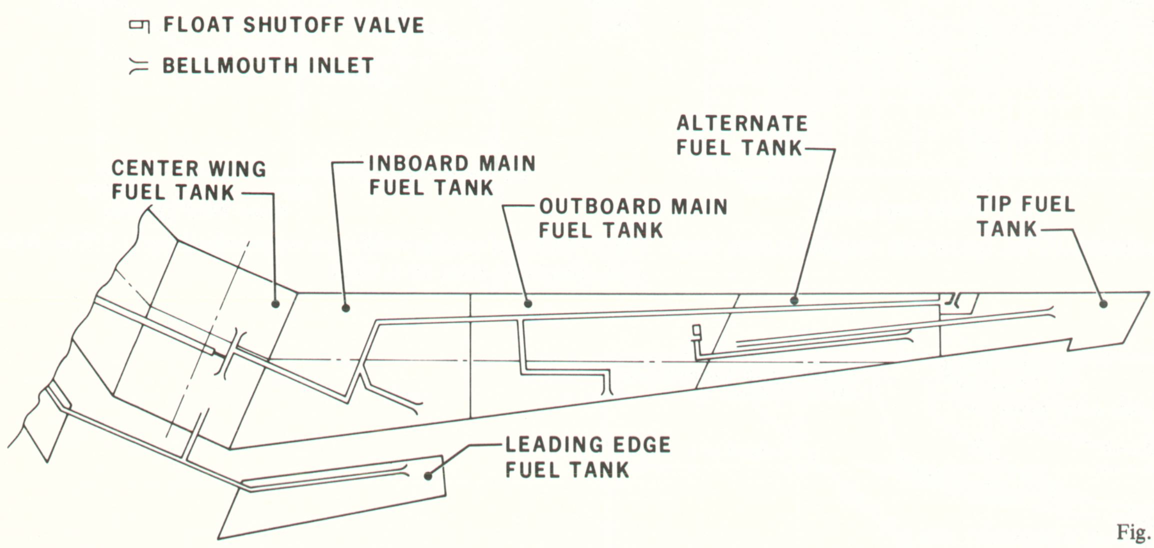

Fig. 8 - DC-8 vent system

Table 1 - Fill Analysis Summary

	Initial Rate, gpm	Estimated Fill Time, min
Emulsified fuel B	285	110
Gelled fuel G	690	46
Liquid JP-4	1530	20.5

Adequate expansion space would have to be provided to prevent fuel from filling the vent system; current regulations require 2% expansion space in a liquid fuel system.

JETTISON SYSTEM - The jettison system on the DC-8 is a gravity flow system. Calculations show the line losses in the jettison piping to exceed the available head.

FUEL TRANSFER SYSTEM - Fuel transfer occurs in several ways in the DC-8 fuel system. Liquid fuel is transferred by gravity flow from the forward auxiliary tank to the center wing tank, and from the outboard compartment of the outboard alternate tank to its inboard compartment (Fig. 10). This type of fuel transfer for the fuels being tested is not feasible.

Tests were conducted on a DC-8 fuel pump with a long inlet line. This fuel pump configuration is used in the liquid fuel system to draw fuel from the center wing tank and to transfer fuel from remote areas of the main tanks to the reservoir boxes. The test pump had to be force primed because it could not draw either the gel or the emulsion through the line even though equipped with a reprime element. After the gel or emulsion was forced into the pump, flow was maintained, but at a low rate. Therefore, a system of remote pickups could not be used with this type pump using one of the fuels tested.

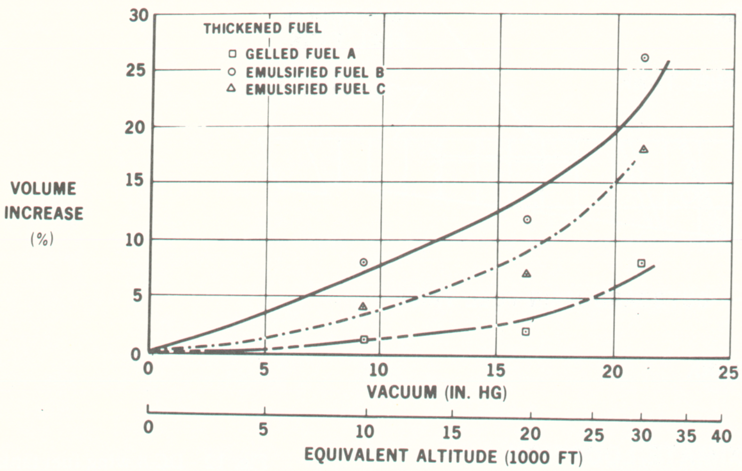

Fig. 9 - Volumetric expansion of thickened fuels with altitude

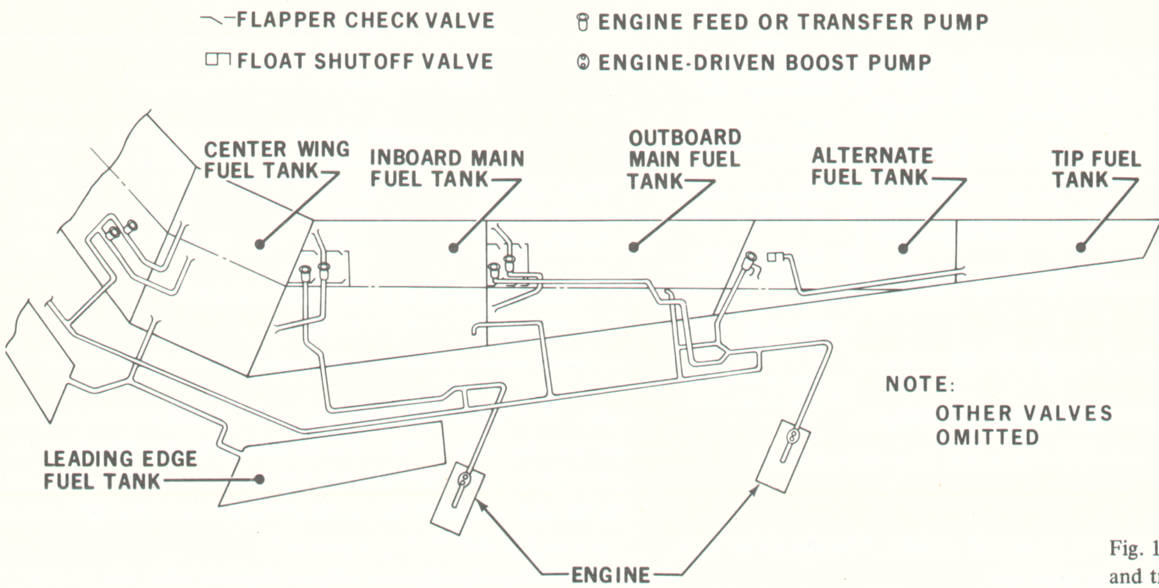

Fig. 10 - DC-8 engine feed and transfer system

All fuel pumps used in the airframe system are of the centrifugal type and impose high shear which could break emulsions or cause gel breakdown.

ENGINE FEED SYSTEM - The engine feed system on the DC-8 normally operates in the suction feed mode. This capability is built into the system to give an added safety advantage in the event of a crash on landing or takeoff in which the fuel feed line is severed. In this condition the tank boost pumps would not be operating, thus preventing the pumping of fuel overboard to feed an existing fire or to increase the probability of fire. Using thickened fuels, this safety advantage would be lost.

The basic engine feed system shown at the top of Fig. 11 includes a centrifugal engine-driven boost pump which could cause fuel breakdown. The use of high pressure tank pumps and the loss of suction feed would obviate the use of the engine-driven boost pump. The FAA requires that fuel be delivered to the engine in an unbroken condition.

A possible configuration for an engine feed system using gelled or emulsified fuels is shown at the bottom of Fig. 11. The fuel/oil heat exchanger upstream of the fuel filter is retained since it is not known at this time what type fuel may be

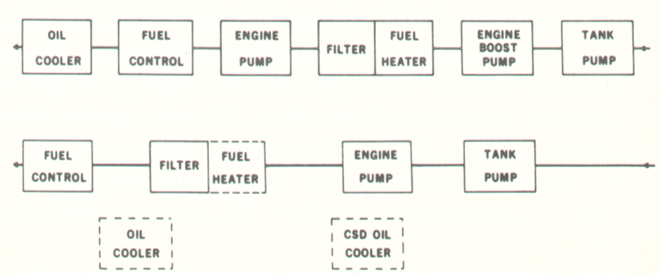

Fig. 11 - Engine fuel systems

used and whether fuel heating may be required. Removing this device from the airframe feed system would reduce the required tank pump output pressure. A heat exchanger in this area would probably be inefficient using the thickened fuel. Little information was found for determining the effects of gelled or emulsified fuels on heat transfer, but the indication is of reduced heat transfer to the thickened fuels. Placing the heat exchanger downstream of the engine-driven main fuel pump would be advisable, because the fuel may be partially broken and heat transfer would be enhanced. Certain DC-8 fuel system configurations reject constant-speed drive oil heat

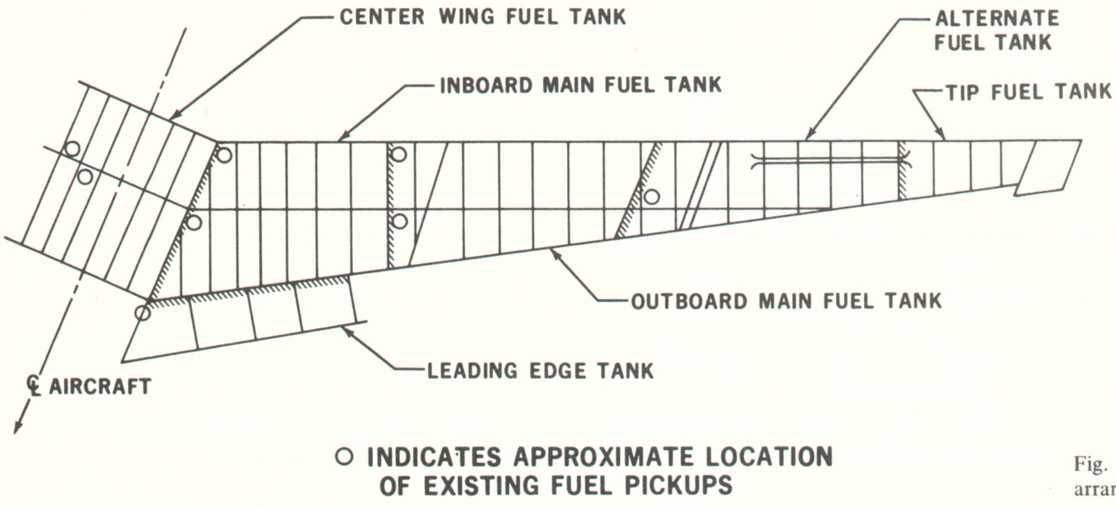

Fig. 12 - DC-8 wing fuel tank arrangement

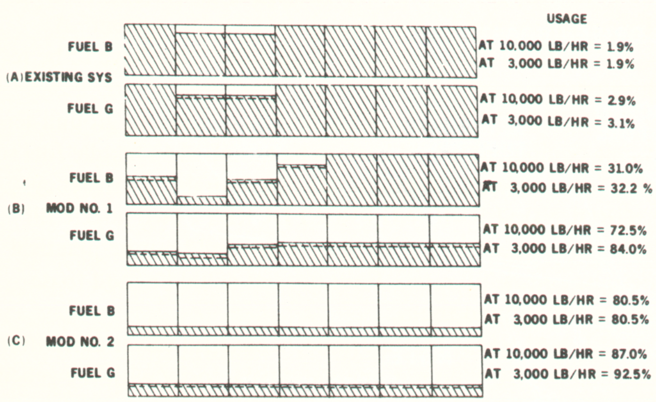

Fig. 13 - Unavailable fuel profile (rear inboard main)

Table 2 - Unavailable Fuel Comparison*

	Liquid JP-4, %**	Emulsion, %	Gel, %
Basic airplane	0.274	97.7	92.2
Modification 1	N/A	73.9	12.9
Modification 2	N/A	17.1	4.0

*Does not include expansion space penalties.
**Percentage of tank volume

to the fuel and some use an air/oil cooler. The use of air as a heat sink appears to be desirable.

TANK FUEL QUANTITIES - Liquid fuel quantities and tank volume are divided into tank trapped, drainable sump, unusable, undumpable, usable, and expansion space. These definitions may not all be applicable in labeling fuel quantities in a gelled or emulsified fuel system. In such a system three quantities provide sufficient description: unavailable fuel, usable fuel, and expansion space. Undumpable fuel may be added if such a system is installed. The terms are self-explanatory.

Fig. 12 shows the arrangement of wing fuel tanks in the DC-8-62. Each tank is divided by partially open bulkheads. Some bulkheads have large lightening holes in the center which permit flow from one bay to the next. Other more highly stressed bulkheads have smaller openings.

An analysis of unavailable fuel was performed to estimate the amount of fuel which would be unrecoverable from the tanks. Tank pumpdown tests were used to give an estimate of remaining fuel in the bay where a pump inlet was located and to aid in estimating the amount of remaining fuel in the bays remote from the pump inlet. The gelled fuel had significant flow through the drain holes, as expected; however, the emulsified fuel would not flow through the drain holes provided.

Unavailable fuel estimates were made for both fuels for three cases. Profiles of the unavailable fuel levels at pump cavitation for the rear half of the inboard main tank are shown in Fig. 13. Levels were calculated for two steady withdrawal rates (3000 and 10,000 lb/hr) corresponding to one-engine cruise and takeoff fuel flows, respectively.

The first case concerns a basic airplane with the existing system (Fig. 13A). Obviously, some modification is necessary to produce a better system.

Minor modifications, limited to additions of components and piping, could be made to the aircraft to increase fuel availability. Structural modifications or other major changes were not considered. The spectrum of possible fuel systems can extend from the basic system to one having a pump inlet in every bay of the tanks. This would be a limiting case for nonstructural modifications.

An intermediate case, referred to as modification 1 (Fig. 13B) was considered. Here, the existing pumps are replaced with positive displacement pumps having an adequate suction capability.

The limiting case, referred to as modification 2 (Fig. 13C) provides each bay with an inlet. This might take the form of small pumps that transfer fuel to a central pickup point.

The results for each case, applied to the whole aircraft, are summarized in Table 2. The ultimate case of modification 2 reduces the unavailable gelled fuel to 4% and the unavailable emulsion B to approximately 17%; unavailable liquid fuel is 0.274 %. Each percent of unavailable fuel increases the dead weight of the aircraft by approximately 1650 lb. Any scheme for recovering fuel must necessarily provide for draining the volume below the stringer line. Approximately 7.5% of the fuel is contained in this volume. The nonfuel weight penalty for modification 2 is estimated to be 968 lb. This weight is for either gel G or emulsion B.

The analysis of unusable fuel did not consider the requirement that the tanks be filled to a level short of liquid fuel capacity. Expansion of fuel due to air expansion and air and vapor evolution (Fig. 9) could mean an additional reduction in fuel volume availability of as much as 20% with emulsion B. Gel A losses due to increased expansion space were 7.4% at 30,000 ft. Cruise altitudes higher than this are common.

The total unavailable fuel volume for emulsion B, considering expansion space loss and assuming a modification 2 recovery, would then be 17% plus 20%, or 37%. This is not directly calculable for gel G because altitude expansion tests were not conducted on that gel formulation, but it is expected to be similar to gel A. The total loss in available fuel volume for gel G is estimated to be 10%.

The minimum undumpable fuel quantity for an aircraft using gelled or emulsified fuel would be determined initially as an increment of fuel above the unavailable level and would be based on increased gross weights. The flow rate from the tanks would be increased to several times the maximum flow rate assumed in the unavailable fuel analysis. The resultant undumpable fuel quantity would depend on the system selected for use.

ENGINE SYSTEM - Testing of engine fuel systems with thickened fuels has been occurring periodically over the last several years. The most recent extensive testing has been with emulsion whose performance in the areas tested was nearly identical to liquid JP-4. Several investigators discovered that a filter plugging problem still exists. This is experienced after the emulsion has been highly sheared and broken. No problems were experienced in the Douglas full-scale fuel system test program when filtering unsheared emulsion B.

The gels have not undergone extensive testing and only minor engine runs have been made with gel G. Combustor testing of gel A for the FAA has been reported. This work, which was limited to a single combustor, showed that gel A, under certain conditions, performed substantially different than the baseline Jet A liquid fuel.

PROBLEM AREAS

Several problem areas have been made apparent during this study and are discussed in the following paragraphs with some solutions offered for consideration. Detail requirements of modifications suggested would have to be determined for a final configuration and would involve the total effects of other modifications and other fuels used in combination.

PUMPS - New pumps of higher capacity would have to be installed. The boost pumps in current use will break the emulsion so a low shear pump would be required for keeping fuel in the engine feed line in an unbroken condition.

Using a positive displacement pump of low shear will possibly require a bypass because of varying flow rate requirements in engine feed and in normal transfer. The problem of shear is then transferred to the bypass device.

Pump reprime remains a problem with the fuels and the centrifugal pump tested. Positive displacement pumps did not exhibit a reprime problem

Conventional aircraft fuel transfer pumps use liquid fuel for cooling and lubrication. The internal bypass cooling flow is highly sheared and is returned to the tank. This flow could free large amounts of fuel from the emulsified form.

GAGING - The gelled and emulsified fuels tested did not flow out of the conventional probes in a satisfactory manner. Teflon surface coating of the probes is not a solution for fluids of high yield value because irregular internal surfaces provide fuel traps. Large plate separations, along with an investigation of fuel dielectric characteristics, or the use of nucleonic gaging, could provide the solution.

FILTERS - Contaminants carried in thickened fuels are expected to be a problem until proper housekeeping is effected in all fuel supply systems and tankage is thoroughly cleaned. Larger filters may be required in the airframe system. A space problem may occur and these filters may have to be relocated.

GROUND SERVICING EQUIPMENT - Current ground servicing equipment would have to be modified to handle fuel so that it is delivered to the aircraft in a desirable consistency.

GROUND SERVICING PROCEDURES - Two nozzle fill systems on medium and large aircraft would not be practical because of low fill rates. Four nozzles could be used to decrease turnaround times.

FILL VALVES - The hydromechanical fill valves currently used on the DC-8 do not operate satisfactorily with the gelled and emulsified fuels tested.

FLOAT SWITCHES - Float switches, currently used to control fuel levels electrically, will not operate satisfactorily with the fuels tested because of small holes which give access to and drainage from small floats.

LINE PRESSURE - Line wall gages may have to be increased commensurate with higher operating, proof, and burst pressure requirements.

JETTISON FLOW RATES - Gravity transfer of fuel will not provide adequate fuel flow to a small number of jettison pumps. This can result in low fuel dump rates for existing pump jettison systems and consequently not permit enough fuel to be dumped. A solution may be found in application of the revised FAA regulations for jettisoning (FAR 25.1001).

PARTS ACCESSIBILITY - Adding new parts to an aircraft in areas where the original design did not provide ready access could present a maintenance problem.

FUEL IN VENT SYSTEMS - Fuel may find its way into vent systems during climbout, maneuvers, or gusting conditions. Thickened fuel may not drain from the vent by gravity and could accumulate with time.

FUEL MANAGEMENT - Tank fuel levels in a liquid fuel system are controlled to provide an optimum fuel weight distribution in the wings. This is done to provide relief for wing bending moments and center of gravity control. Transfer of fuel is semi-automatic and requires little crew attention. The addition of more pumps or the smaller packaging of fuel supplies to increase fuel utilization will result in more complex management procedures.

DISPATCH INOPERATIVE (MINIMUM EQUIPMENT) LIST - The list of equipment which may be inoperative at takeoff and the compensating conditions applied may become a complication with the use of thickened fuels. Redundancy in system modifications to attain a satisfactory level of safety will be required and will add a weight penalty. Dispatch delays could be substantial without a required level of redundancy or system independence.

RELIABILITY - Solutions so far discussed generally require the addition of parts and thus cause an inherent decrease in reliability.

SYSTEMS ANALYSIS AND TESTING - The systems testing and analyses which were performed indicate that much work needs to be done on any fuel chosen for development. A large amount of testing will be required to provide design data for retrofit analyses and for new designs. An acceptable confidence level will have to be developed in understanding the flow characteristics of the fuel selected in order to extrapolate test data into untested regions. Complete coverage of the required performance regions with a test program can provide the necessary information.

EXPERIMENTAL GROUND TEST PROGRAM

An experimental ground test program which may be conducted on any airplane to evaluate airframe and engine fuel systems performance when operating with a candidate gelled and/or emulsified fuel was outlined. The object of this test program is not to certify an aircraft for use with a particular fuel, but to qualify the system by obtaining an adequate confidence level that the aircraft could be used with the fuel in a flight test program. It is assumed that the flight test program will start with the candidate fuel being used in only part of the system, (for example, one tank set/engine combination) and that inflight environmental effects will be evaluated during the remainder of the flight test program. Additional tests were outlined which will examine an aircraft for compatibility with use of a candidate fuel.

In general, these tests examine the basic airframe fuel subsystems: fill, vent, jettison, transfer, and engine feed for satisfactory operation. The engines are operated with a candidate fuel to examine the engine fuel systems, control systems, and endurance factors. A complete teardown inspection is recommended following the test series.

SUMMARY

The results of this investigation indicate that the DC-8-62 liquid system is not compatible with the gelled and emulsified fuels tested. Extensive system modifications would be necessary if these fuels were to be used in service. An empty weight increase would result along with a decrease in available fuel volume. Development of new systems would be necessary in some cases. A ground test program has been outlined to evaluate system performance and compatibility with new fuels. Details of this program can be found in the final report*.

This program is being followed by an economic analysis to compare the estimated dollar costs (in the 10 fiscal years 1971-1980) of using gel G in all United States air carrier jet aircraft against the use of conventional jet fuels.

ACKNOWLEDGMENT

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*A. T. Peacock, R. F. Hazelton, L. S. Gresko, and L. D. Christensen, "A Study of the Compatibility of a Four-Engine Commercial Jet Transport Aircraft Fuel System with Gelled and Emulsified Fuels." Federal Aviation Administration Report NA-70-11 (DS-70-1) for Contract No. FA68NF273, January 1970.

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